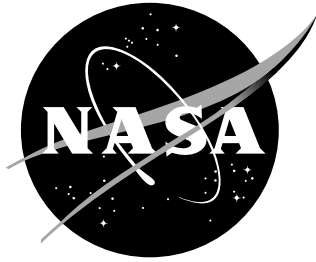


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Thermal Nondestructive Characterization of Corrosion in Boiler Tubes by Application of a Moving Line Heat Source

*K. Elliott Cramer and William P. Winfree
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January 2000

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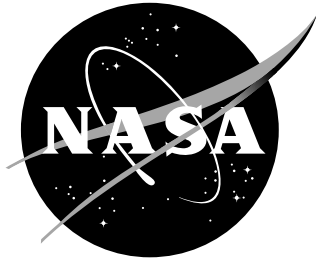
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ABSTRACT

Wall thinning in utility boiler waterwall tubing is a significant inspection concern for boiler operators. Historically, conventional ultrasonics has been used for inspection of these tubes. This technique has proved to be very labor intensive and slow. This has resulted in a "spot check" approach to inspections, making thickness measurements over a relatively small percentage of the total boiler wall area.

NASA Langley Research Center has developed a thermal NDE technique designed to image and quantitatively characterize the amount of material thinning present in steel tubing. The technique involves the movement of a thermal line source across the outer surface of the tubing followed by an infrared imager at a fixed distance behind the line source. Quantitative images of the material loss due to corrosion are reconstructed from measurements of the induced surface temperature variations. This paper will present a discussion of the development of the thermal imaging system as well as the techniques used to reconstruct images of flaws. The application of the thermal line source, coupled with this analysis technique, represents a significant improvement in the inspection speed for large structures such as boiler waterwalls while still providing high-resolution thickness measurements.

A theoretical basis for the technique will be presented thus demonstrating the quantitative nature of the technique. Further, results of laboratory experiments on flat panel specimens with fabricated material loss regions will be presented to demonstrate the capabilities of the technique. Additionally, the results of applying this technology to actual waterwall tubing samples will be presented.

1. INTRODUCTION

Recent developments have shown the advantages of infrared (IR) thermography for the detection of corrosion and disbonds in aircraft structures^{1,2,3}. The techniques used have typically involved the application of heat with an IR source and imaging the induced temperature change with an IR imager. This offers a rapid method for detecting corrosion and quantifying its extent in single layer structures. In that application, the heating and imaging components of the system remain stationary during the measurement cycle. Two disadvantages of that technique are the expense of the infrared imager and the large power requirement for the infrared heater.

This paper examines an alternate method for thermographically obtaining the same data. It is patterned after a technique described by Maldague⁴ where a sample moves at a constant velocity past a fixed linear heat source and is observed by an IR imager. Maldague demonstrates that the method is effective for the detection of disbonding in laminated samples. A distinct advantage of Maldague's method over typical thermographic techniques is that the IR heater is held close to the object of interest, enabling more efficient coupling of the energy into the specimen and reducing the power requirements. An additional advantage is that a linear array detector can replace the imager, significantly reducing the cost of the system.

Presented here are results from an alternate implementation of Maldague's method where the specimen is stationary and the line heat source and IR imager are translated together at a constant velocity. From the output of the IR imager, an image is reconstructed which represents the induced temperature changes at a fixed distance behind the line heat source. This unique approach to thermography enables rapid inspection of large structures while maintaining the same level of sensitivity characteristic of conventional thermography.

This paper will discuss a technique originally developed to detect material loss due to corrosion in aircraft fuselage skins. Included will be the results of laboratory measurements on specimens with fabricated thinning to simulate material loss and a theoretical basis for relating the amount of thinning to the induced temperature change. An extended application of this technique beyond aircraft structures, to the rapid detection of wall thinning in utility boiler waterwall tubing samples in a laboratory setting, will also be discussed.

2. EXPERIMENTAL TECHNIQUE

The current implementation of the scanned line source and imager is shown in Figure 1. The IR imager is a commercial radiometer with a cooled 256x256-element InSb (Indium - Antimonide) focal plane array detector. The radiometer's noise equivalent temperature difference (NEDT), cited by the manufacturer, is 0.025°C when operating the detector in the 3 to 5 micrometer wavelength range. The radiometer produces images at both 30 frames per second output (video frame rate, in an RS170, format compatible with standard video equipment) and 60 frames per second output in a 12-bit, RS422 digital format. External germanium optics, consisting of a wide-angle lens, were used to increase the system field-of-view by a factor of approximately two. This lens has a field-of-view of 22° in both the horizontal and vertical direction.

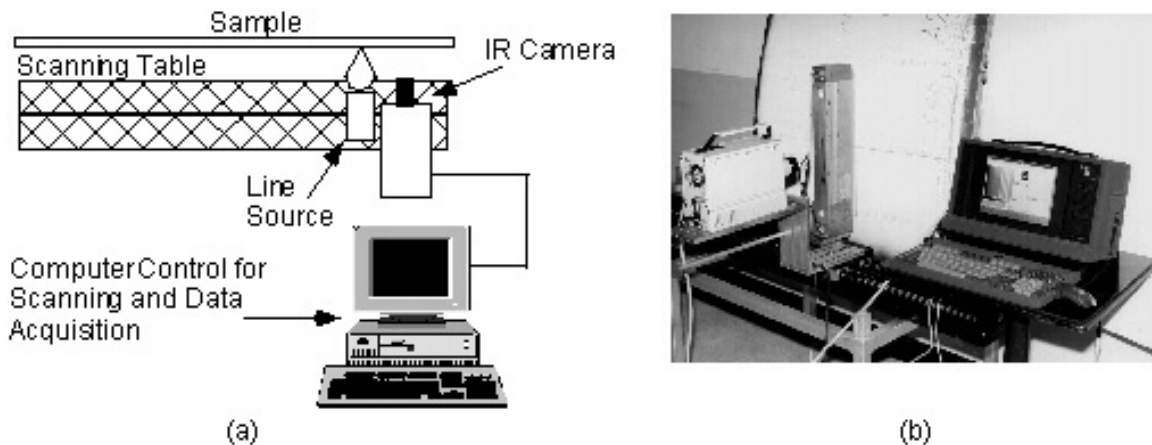


Figure 1 – (a) Schematic and (b) photograph of experimental setup used to implement moving line source technique.

An approximate line of heat (40.6 cm in length and 0.25 cm in width) is obtained by focusing a 1000-watt quartz lamp with an elliptical reflector behind the quartz tube onto the specimen. The heat source and the IR imager are attached to a commercially available linear scanning bridge. Quantitative time based analysis requires synchronization between the IR imager, the heat source and the scanning table. This synchronization is achieved by computer control of the application of heat, motion of the scanning table and data acquisition. The computer can provide any scanning speed up to 30.5 cm/sec. For all cases presented in this paper the maximum surface temperature change of the sample never exceeds 15°C above ambient.

For reflective surfaces, it is necessary to apply an emissivity enhancing coating. Most paints have high emissivity, therefore if the specimen is painted, regardless of color, no additional surface coating is necessary. Metal samples, which are normally unpainted, require the addition of an emissivity enhancing coating. The samples used in this study were treated with either water washable, nontoxic paint, or flat black aerosol lacquer.

The digital data from the radiometer is acquired and stored at 60 frames-per-second in a real-time image processor board in the control computer. The image processor board has 256 megabytes of image memory available for storage and is capable of real-time floating point processing of the incoming data. The imaging camera moves with the heat source, enabling data acquisition at a fixed distance from the source. From a set of acquired images, a single image is then reconstructed that represents the induced temperature change at a given distance from the heat source. The reconstructed image is typically 256 pixels high and up to 1200 pixels wide (depending on the physical length of the sample scanned and the speed of the scanner). This reconstruction is currently accomplished by post processing the set of acquired images using the host computer. All of the data presented in the remainder of the paper (unless otherwise noted) were reconstructed in this manner.

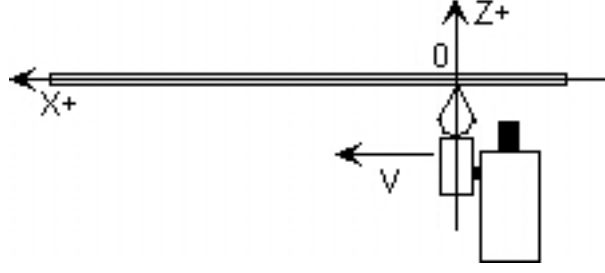


Figure 2 – Geometry used for the development of steady state analytical solution.

3. STEADY STATE ANALYTICAL SOLUTION

For a moving linear heat source the temperature distribution in a semi-infinite media with an infinitely long line source moving along the surface, in the x-direction, from time equal to $-\infty$ to t is given by⁵:

$$T(x, z, t) = \frac{q}{\pi K} e^{-v(x-vt)/2\kappa} K_0 \left[\frac{v((x-vt)^2 + z^2)^{1/2}}{2\kappa} \right], \quad (1)$$

where v is the velocity of the moving line source (Figure 2), K and κ are the thermal conductivity and diffusivity respectively and q is the rate of heat emitted by the line source per unit length. $K_0(x)$ is the modified Bessel function of the second kind of order zero. From this expression, temperature at the heated surface (at $z = 0$) of a layer of thickness L is found to be

$$T(x, t) = \frac{q}{\pi K} e^{-v(x-vt)/2\kappa} \left(K_0 \left[\frac{v|x-vt|}{2\kappa} \right] + 2 \sum_{n=1}^{\infty} K_0 \left[\frac{v((x-vt)^2 + (2nL)^2)^{1/2}}{2\kappa} \right] \right) \quad (2)$$

In the frame of reference moving with, and centered on the heat source, the temperature at the surface is given by

$$T(x) = \frac{q}{\pi K} e^{-vx/2\kappa} \left(K_0 \left[\frac{v|x|}{2\kappa} \right] + 2 \sum_{n=1}^{\infty} K_0 \left[\frac{v(x^2 + (2nL)^2)^{1/2}}{2\kappa} \right] \right). \quad (3)$$

This solution for the heat equation best represents the induced temperature change in the region near to the source or is the near field solution.

An alternate representation of the temperature profile is derivable which best represents the region far from the source or the far field solution. The form of the equation is given by

$$T(x, z) = \frac{q}{Lvpc} \left[e^{-\frac{v(x+|x|)}{2\kappa}} + 2v \sum_{n=1}^{\infty} \cos\left(\frac{n\pi z}{L}\right) e^{-\frac{vx + |x| \sqrt{(2n\pi\kappa/L)^2 + v^2}}{2\kappa}} \right] \frac{2\kappa}{\sqrt{(2n\pi\kappa/L)^2 + v^2}}, \quad (4)$$

where ρ and c are the density and specific heat respectively. Examination of Equation 4 indicates that when the summation is approximately equal to zero, the temperature becomes a constant, $q/(Lvpc)$, if x is negative. For lower velocities ($2vL/\kappa < 1$), the condition necessary for the summation to be approximately zero is

$$x < \frac{2\kappa}{v - \sqrt{(2\pi\kappa/L)^2 + v^2}} \approx \frac{L}{\pi}. \quad (5)$$

At ($2vL/\kappa > 1$), the condition where the summation is zero is approximated when the distance behind the line source is equal to the thickness of the plate. When this occurs, the temperature in the far field behind the source becomes

$$T = q/(Lvpc), \quad (6)$$

and thus is inversely proportional to the thickness of the layer. Figure 3 shows the spatial dependence of the temperature for several different values of Lv/κ . As can be seen from Figure 3, the temperature rapidly approaches $q/(Lvpc)$ in the region behind the heat source.

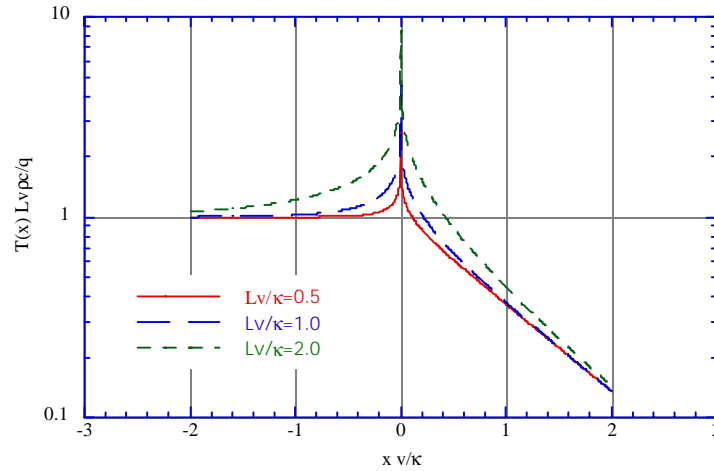


Figure 3 – Analytical solution for induced temperature change around moving linear line source.

4. NUMERICAL SOLUTION OF TRANSIENT TEMPERATURE PROFILE FOLLOWING APPLICATION OF LINEAR HEAT SOURCE

For a thin layer of high diffusivity material, when the heat source has been on long enough to approximate having been on from $-\infty$ to the present, the temperature rapidly falls to a constant value behind the heat source. This is typically a more limiting constraint, than the constraint imposed by Equation 5. An accurate approximation of this induced temperature change at distances $3L$ or further from the source is given by

$$T(x, x_0) = \frac{q}{Lv\rho c} \frac{1}{2\sqrt{\pi}} \int_0^{xv/\kappa} \frac{e^{-(x_0v/\kappa - p)^2/4p}}{\sqrt{p}} dp, \quad (7)$$

where x_0 is the observation point. The integral in Equation 7 is approximately equal to $2(\pi)^{1/2}$ for $x \gg x_0$ resulting in a limit of $q/Lv\rho c$. Typical profiles for the induced temperature change following the linear heat source being turned on at $x = 0$ are shown in Figure 4. As expected, when the distance from the source increases, the distance the source must travel before the induced temperature change becomes constant increases.

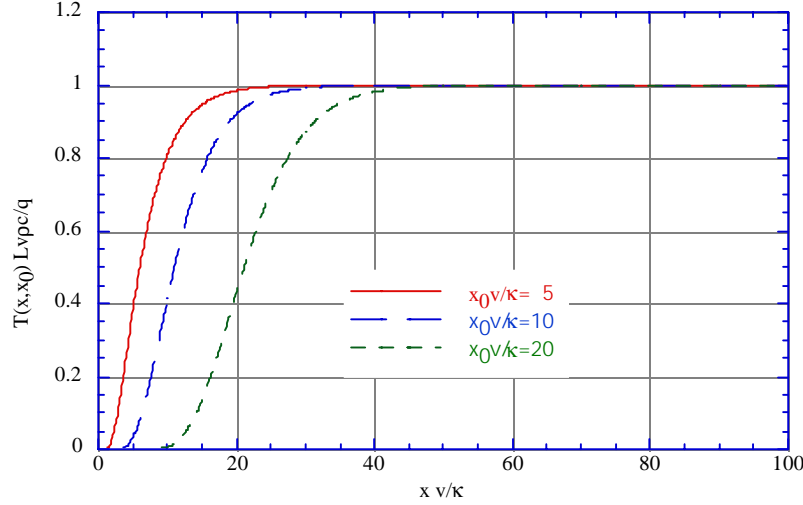


Figure 4 – Temperature change induced by moving linear heat source as a function of position at a fixed distance x_0 behind the source.

The distance that is required for the temperature to achieve a value of $q/Lv\rho c$ is also significant when considering variations in the thickness of the plate. A reasonable approximation for small changes in the plate's thickness is modulating the amplitude of the flux of the thermal line source by the inverse of the thickness of the plate. Using Equation 7, it is easy to find the response for a plate when the source is turned on and off for three periods. The results are shown in Figure 5. These results indicate that as the distance between the source and observation point increases the resolution for detection of variations in thickness decreases. Velocity in Figure 5 contributes to both x_0v/κ and xv/κ . Independent calculations indicate that as the velocity increases, the spatial resolution improves for a fixed distance between the observation point and the source.

5. EXPERIMENTAL MEASUREMENTS OF SPATIAL RESOLUTION SPECIMENS

To investigate the relationship between the velocity of the moving system and the separation between the observation point and the heat source, samples were created with multiple regions of material loss. Figure 6 shows a schematic of one of these samples. Each sample is 91.4 cm long, 30.5 cm. wide and 0.30 cm. in thickness. High carbon steel was chosen as the material for these samples to allow the effects of variations in speed to be investigated over the reasonably small velocity range of the scanning table and to appropriately simulate boiler waterwall tubing. Data was collected for speeds ranging from 2.54 cm/sec to 12.7 cm/sec and for separation distances between the observation point and the heat source ranging from 1.9 cm. to 19 cm. It is to be noted that the minimum separation distance of 1.9 cm. is a physical constraint dependent upon the current heat source and the field-of-view of the IR imager.

Figure 7 shows two images at two different speeds, 2.54 cm/s, and 10.1 cm/s both with a fixed separation distance of 1.9 cm. As the speed of the moving line increases the images become sharper due to a reduction in inplane diffusion between when the heat is applied and when the data is collected. Figure 8 shows a single line of data across a portion of the sample for three different speeds. These measurements are qualitatively in good agreement with the results of the previous section. It is

notable that for all speeds, the amplitude of the modulation is inversely proportional to the thickness change. Based on this data, a speed of 10.1 cm/s is required for accurate measurements of the thickness of slot 1.27 cm wide in this specimen.

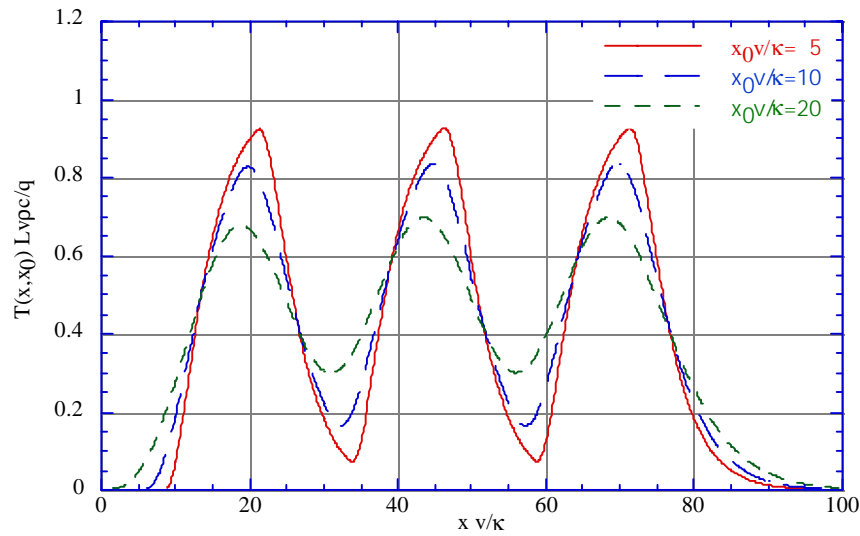


Figure 5 – Temperature change induced by moving linear heat source which is turned on and off for three periods of 25. Plotted is temperature at a fixed distance x_0 behind the source.

A similar effect can be observed when keeping the speed constant and varying the separation distance between the line of heat and the observation point. Figure 9 shows two images taken at the same speed (5.0 cm/s) but at two different separation distances: 2.1 cm and 14 cm. As the separation distance is increased the images begin to blur due to diffusion effects. Figure 10 shows a single line of data across a portion of the sample for three different separation distances: 2.1 cm, 8.0 cm and 14.0 cm. Figures 9 and 10 show good qualitative agreement with the theoretical results of the previous section. These results indicate that if the separation distance becomes too great, quantitative information is lost and the effects of diffusion again dominate. Additionally, this indicates the potential for using this technique for diffusivity measurements.

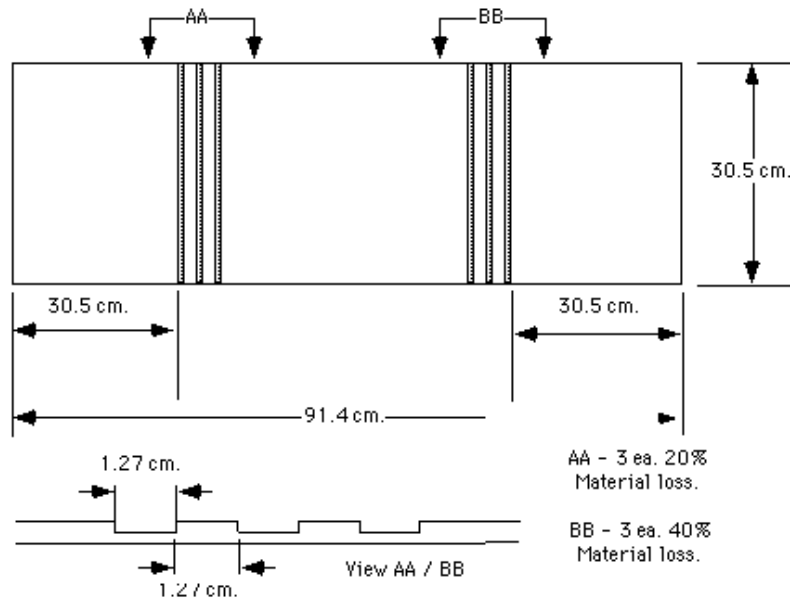


Figure 6 – Spatial resolution specimen for thermal line scanner.

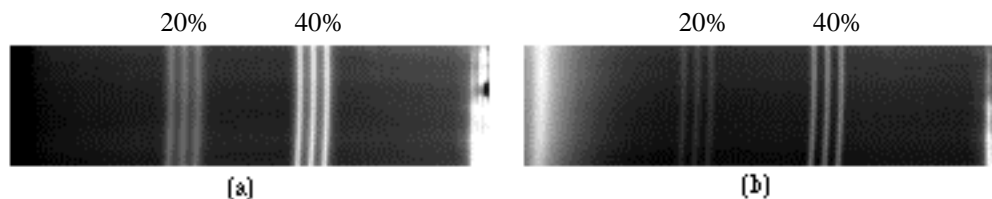


Figure 7 – Images of steel resolution sample at a separation distance of 1.9 cm and two different speeds (a) 2.5 cm/s and (b) 10.1 cm/s.

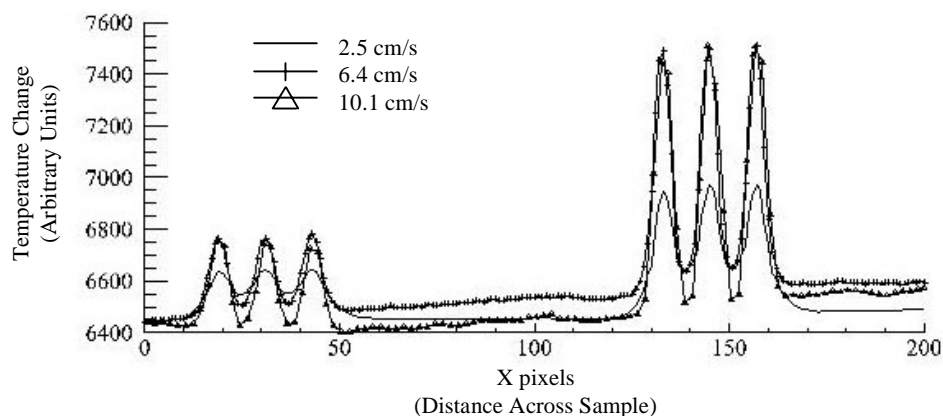


Figure 8 – Three single lines of data at three speeds showing the relationship between speed and diffusion effects for a steel resolution sample.

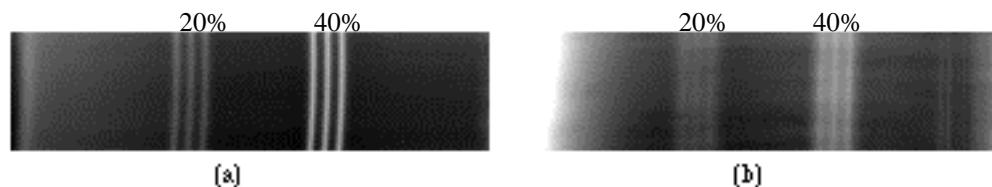


Figure 9 – Images of the steel resolution sample at a speed of 5.0 cm/s and separation distances of (a) 2.1 cm and (b) 14 cm.

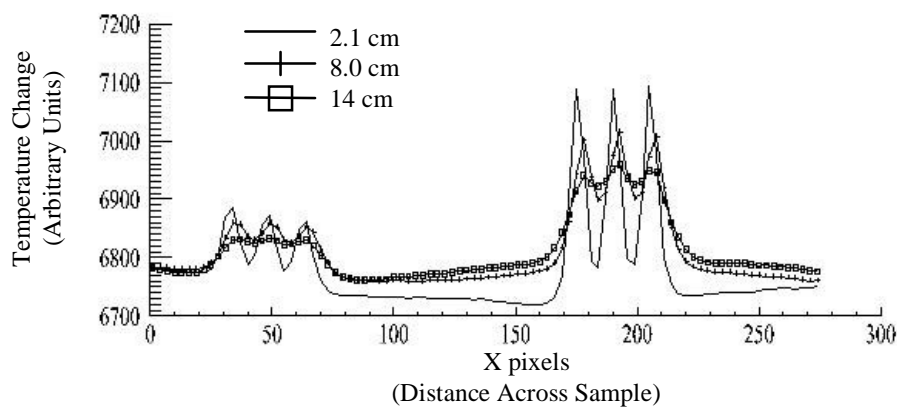


Figure 10 – Three single lines of data at three separation distances showing the relationship between distance behind the line of heat and diffusion effects for a steel resolution sample.

6. APPLICATION OF TECHNIQUE TO WATERWALL TUBING

Next, the technique was applied to an actual waterwall tube section. The sample had been removed from a commercial power plant and was then sectioned into manageable sized samples. The sample inspected was 116.8 cm in length, 26.7 cm in width with tubes of outside diameter 3.2 cm and nominal wall thickness of 0.7 cm. Defects were artificially introduced into the sample by removing the entire wall thickness on one side of the sample to provide an access port, then machining material loss regions on the now exposed inside walls of the tubing. Different sizes and depths of defects were introduced into the sample to provide a representative selection of the material losses that may be found in operational boilers. Figure 11 provides a schematic on a typical laboratory sample of steel tubing showing the pattern of defects introduced. The defects were produced in the crown region of the tubes ($\pm 20^\circ$ of top-dead-center) only. Since the majority of the material loss in boiler tubes occurs near the crown, this is a good approximation of boilers in service⁶.

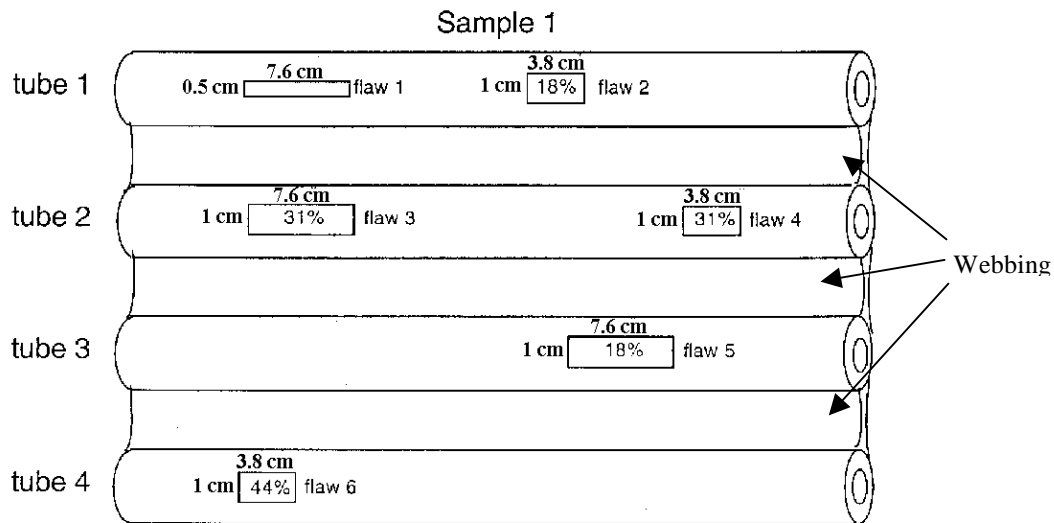


Figure 11 – Schematic of waterwall tubing sample showing fabricated flaw sizes (width and length) and amount of material removed as a percent of total wall thickness. The sample consisted of a total of 6 tubes, of which only the 4 center tubes where defects were fabricated are shown.

The results of scanning the waterwall tube sample are shown in the image in Figure 12. The sample was scanned at a speed of 6.3 cm/s and the separation distance was 2.5 cm. All the machined defects can be clearly detected in the resulting image. Since material loss does not typically occur in the webbing between the tubes (dark band in Figure 12) these regions of the thermal image are ignored. Further it is possible to calibrate the results of the thermal imaging to measure tube thickness at points along the crown of the tube. Mechanical thickness measurements were made at various locations along tube number one (see Figure 12). These measurements were then used to calculate a calibration constant (vpc/q) for equation (6). This constant was then be applied to the data from the other three tubes to obtain maps of their thickness. Figure 13 shows a plot of the thickness of each of the tubes verses position. A region of the thermal image equal to 20 degrees of the tube crown was averaged to produce the thickness plots. Initial comparisons with conventional ultrasonic measurements taken at locations along the tubes agree well with the thermal results.

7. CONCLUSIONS AND FUTURE DIRECTIONS

A noncontacting thermal NDE technique has been developed which employs a moving line heat source and is capable of imaging material loss in steel structures such as utility boiler waterwall tubing. This technique has been shown to effectively detect thinning in steel laboratory samples designed to determine the spatial resolution of the system. A steady state solution for the induced thermal change has been developed. It has been shown that when the steady state condition is achieved, the induced temperature change is inversely proportional to the thickness of the material at an observation point more than one

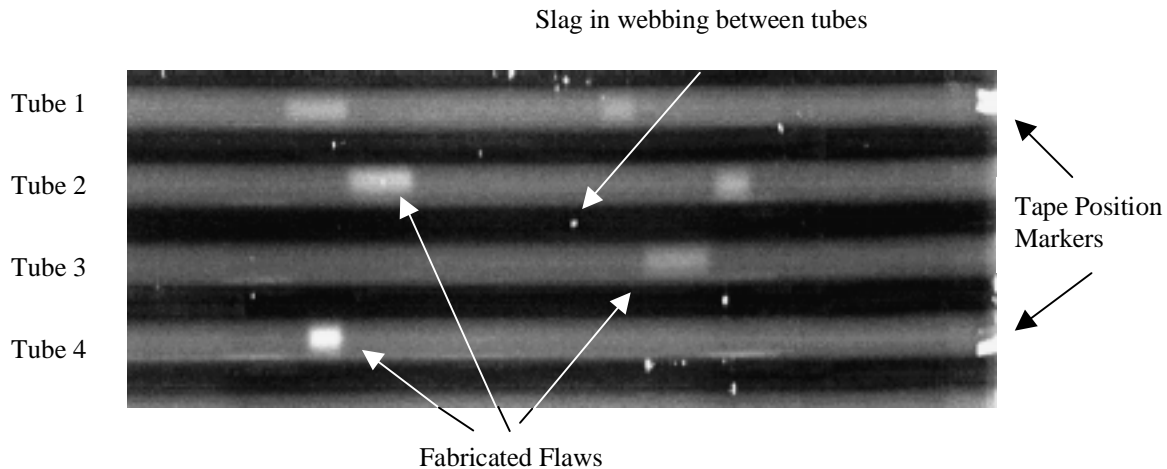


Figure 12 – Reconstructed thermogram of waterwall tubing sample showing the detection of fabricated flaws.

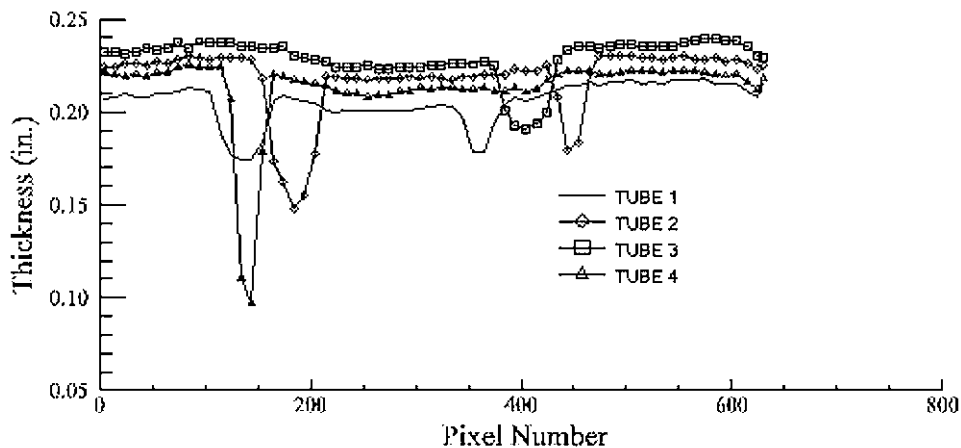


Figure 13 – Thickness information from three waterwall sample tubes calibrated using measurements from tube 1.

thickness of the plate behind the linear source. A more critical constraint on thickness measurements with this technique is the time or distance required to achieve a steady state condition. The experimental results are in agreement with theoretical results.

Application of the technique to laboratory samples of waterwall tubing has yielded promising results. Additionally, qualitative agreement was seen in initial comparisons of the calibrated thermal data with conventional ultrasonics. Further ultrasonic measurements are planned allowing a detailed comparison of conventional results with this new method. This will help in determining the limits of this technique for application to waterwall tubing.

In the future, additional analysis methods that take advantage of the data acquired at multiple observation points should significantly improve the results and enhance quantitative analysis of the material loss. One such analysis method could involve reconstructing a series of images from the data acquired, each image at a different distance from the heat source. These images could then be treated as a time series and variations in the heat propagation rates could be explored by such analysis methods as a time derivative. Further, for this technique to be applied in a practical manner additional work will be done on field implementation. A robotic scanner that could efficiently transport the heat source and imager over large areas of an aircraft, or utility boiler, shows promise of great potential.

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